Groundwater protection in fractured media: a vulnerability-based approach for delineating protection zones in Switzerland

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Abstract A vulnerability-based approach for delineating groundwater protection zones around springs in fractured media has been developed to implement Swiss water-protection regulations. It takes into consideration the diversity of hydrogeological conditions observed in fractured aquifers and provides individual solutions for each type of setting. A decision process allows for selecting one of three methods, depending on the spring vulnerability and the heterogeneity of the aquifer. At the first stage, an evaluation of spring vulnerability is required, which is essentially based on spring hydrographs and groundwater quality monitoring. In case of a low vulnerability of the spring, a simplified method using a fixed radius approach ("distance method") is applied. For vulnerable springs, additional investigations must be completed during a second stage to better characterize the aquifer properties, especially in terms of heterogeneity. This second stage includes a detailed hydrogeological survey and tracer testing. If the aquifer is assessed as slightly heterogeneous, the delineation of protection zones is performed using a calculated radius approach based on tracer test results ("isochrone method"). If the heterogeneity is high, a groundwater vulnerability mapping method is applied ("DISCO method"), based on evaluating discontinuities, protective cover and runoff parameters. Each method is illustrated by a case study.

Keywords Fractured rocks · Groundwater protection zones · Springs · Vulnerability Mapping · Switzerland

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Introduction

Fractured aquifers represent an essential groundwater resource for large parts of the world. In Switzerland, where more than 80% of drinking water is provided by groundwater, fractured media cover 78% of the land surface and supply approx. 35% of the exploited groundwater. Other water-bearing formations are porous, unconsolidated aquifers (6% of the land surface) and karst aquifers (16% of the land surface), which provide some 45 and 20% of the exploited groundwater respectively (Tripet 2005).

The delineation of protection zones in fractured aquifers is a challenging task due to the heterogeneity and anisotropy of hydraulic conductivities, which makes prediction of groundwater flow organization and flow velocities difficult (Berkowitz 2002). Important efforts are currently being made by researchers in various fields of hydrogeology to gain better understanding of groundwater flow in fractured rocks (Krasny et al. 2003), but significant improvement is still needed in the field of groundwater protection (Bradbury 2002).

To date, several approaches have been proposed for the delineation of protection zones in fractured rocks by

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applying basic fixed-radius methods to groundwater flow models (Bradbury et al. 1991; Lipfert et al. 2004). Although the application of numerical models may provide the most accurate results for well-documented sites, insufficient data often mean that such quantitative approaches are difficult to apply. Methodologies for delineating groundwater protection zones must be adapted to different site characteristics and to the type of data available. A multi-stage approach, beginning with a general characterization of the hydrogeological context, which then applies adequate field techniques and finally selects the most appropriate method for protection zone dimensioning should be considered in order to obtain reliable results in any type of setting (Heath 1995; Barton et al. 1999).

The approach presented here sets out to delineate protection zones for public drinking water supply in fractured rocks in Switzerland. Groundwater is essentially extracted from springs linked to shallow aquifers often located in mountainous regions. They typically provide moderate to low yields of between 20 and 500 L/min. The springs are mainly located in areas where pollution sources are related to cattle pasturing, mountain farming and tourism, although in some areas, especially in the Swiss Plateau, pollution hazards related to intensive farming and industry may also exist. Delineation of protection zones is required for a large number of water supplies as each community generally relies on several springs. It is therefore imperative that the methodology is affordable in terms of cost and is technically feasible for private consulting hydrogeologists. To promote the national harmonization of protection zoning, the approach must also be verifiable, reproducible and applicable to any type of fractured aquifer exploited in Switzerland. The approach presented in this paper is assumed to achieve these objectives.

Characteristics of fractured aquifers in Switzerland

Fractured non-karst aquifers exploited in Switzerland are distributed across the Alps, the Prealps and the Swiss Plateau (Fig. 1). The variety of sedimentary, igneous and metamorphic rocks located in diverse tectonic contexts coincides with different types of hydrogeological settings (Table 1):

– Weakly fractured sandstones, marls and conglomerates represent the bedrock of the Swiss Plateau (Plateau Molasse). The hydraulic conductivity of these deposits measured on samples and boreholes is low to moderate (10^{-7}–10^{-5} m/s) with a maximum of 10^{-4} m/s in poorly consolidated coarse sandstone (Keller 1992). Preferential flow is observed along bedding planes and fractures. Enhanced hydraulic conductivity is also linked to the presence of high secondary interstitial porosity in the uppermost weathered zone, which may reach a thickness of several metres (Parriaux 1981). Such aquifers are frequently associated with shallow water-bearing Quaternary deposits (fluvio-glacial channels, sandy or gravely moraine deposits), which may constitute the main storage capacity of these mixed systems. Although many tracer experiments have been performed in this type of aquifer for the delineation of protection zones, little information has been published

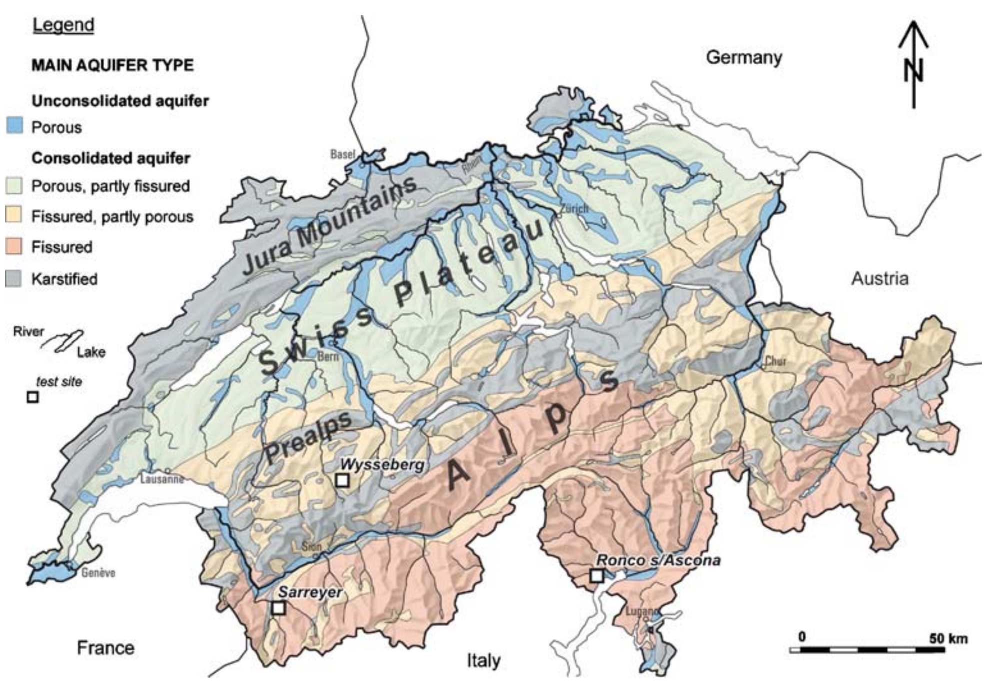

Fig. 1 Hydrogeological sketch of Switzerland with location of the three test sites Wysseberg, Sarreyer and Ronco sopra Ascona

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Table 1 Groundwater resources in fractured media: geological and hydrogeological conditions in Switzerland

Lithology	Porosity		Flow type	Geographic distribution
	Interstitial	Fracture		
Sandstones, conglomerates, marls (Plateau Molasse)[a]	Low to moderate, primary and secondary (alteration, dissolution)	Low	Dual porosity (interstitial and/or fractures)	Swiss Plateau, synclines of the Jura Mountains
Sandstones, conglomerates, marls, schists, siliceous limestones, non-karstic dolomites (Among others: Subalpine Molasse, flysch)[a]	Low to insignificant, mostly secondary; may be significant near the ground surface (alteration)	Low to moderate, locally high in the presence of dissolution	Mostly in fractures	Southern border of the Plateau, Prealps, Alps
Granites, gneiss, schists, basic to ultra-basic igneous rocks, sandstones (Among others: crystalline units, permo-carboniferous series of the penninic nappes)[a]	Insignificant	Low to moderate	In fractures	Alps

[a] Structural units or examples

to date. In general, tracer test results imply low mass recovery and velocities not exceeding a few metres per day (Wernli and Leibundgut 1993).

– The same rock types located at the southern border of the Swiss Plateau (Subalpine Molasse) show contrasting hydrogeological properties compared to the Plateau Molasse. The influence of the Alpine orogenesis resulted in the exhumation, folding and faulting of more consolidated rocks, due to diagenetic processes (Keller 1992). Interstitial porosity is low, while fracture porosity is globally moderate but may be enhanced by dissolution of carbonate minerals, especially along discontinuities, with a resulting enhancement of the aquifer heterogeneity. In such contexts, flow velocities of up to several hundreds of metres per day have been determined by tracer experiments (compiled in Pochon and Zwahlen 2003). To the south of the Subalpine Molasse, flysch consisting mainly of sandstones, sandy limestone and shales show similar hydrogeological properties, with dominant fracture porosity enhanced locally by dissolution processes (Basabe-Rodriguez 1982). Slope instabilities and landslides are frequent in these regions (Lateltin et al. 1997) and groundwater resources may occur in both displaced fractured rock mass and Quaternary deposits.
– Igneous and metamorphic rocks represent the backbone of the central and southern Swiss Alps. In such rock types, groundwater essentially flows along fractures as matrix permeability is negligible. Dissolution processes are not significant and flow organization is predominantly dependent on fracture networks generated by tectonics (NRC 1996). Hydraulic conductivities determined in the Swiss Alps are generally low, for example between 10^{-7} and 10^{-5} m/s according to slug tests performed in shallow depth boreholes (Beatrizotti 1996; Ofterdinger 2001) and between 10^{-11} and 10^{-6} m/s based on methods which take inflows along gallery sections (Maréchal 1998; Ofterdinger 2001) into account. However, very permeable zones linked to intensely fractured zones are observed along tunnels (Jamier 1975; Dubois 1991), confirming the importance of heterogeneity and the existence of locally high flow velocities in such aquifers. In addition, a decompression zone, linked to post glacial relaxation and gravity forces, is often described in the Alps (Cruchet 1985; Maréchal 1998). It accounts for enhanced fracture aperture and permeability in the first tens of metres below the surface. Crystalline Alpine rocks do not exhibit a shallow zone of high porosity due to chemical weathering as observed in other climatic regions (Taylor and Howard 1998). This can be explained by intense glacial ablation processes across the region which were active until less than 10,000 years ago (Jäckli 1970).

Groundwater protection zoning in Switzerland

Regulations and requirements

According to the Swiss Federal Water Protection Ordinance (WPO 1998), the strategy in force for the protection of groundwater quantity and quality is based on prevention. Groundwater protection zones must be defined in the water catchment area of each groundwater supply used for public drinking water. The aim of the protection zones (S1, S2 and S3) is mainly to protect the drinking water against contaminants, including pathogenic micro-organisms such as protozoa, bacteria and viruses. Moreover, a code of practice regulates all potentially polluting activities or adverse influences threatening groundwater quality in each zone (Table 2). In unconsolidated porous media, the delineation of protection zones is based on groundwater residence time. The limits of the different zones are approximately concentric around the groundwater well, with the degree of land use restriction decreasing with increasing distance from the source (Fig. 2a). In karst and fractured media, flow velocities are often highly variable in time and space. Under these circumstances, the delineation of protection zones based on the hypothesis of uniform flow velocities may or may not be justified (Fig. 2b, 2c). For this reason, the WPO requires the degree of groundwater vulnerability to be considered as a basic criterion for the delineation of protection zones in these aquifer types. Specific methodological approaches and guidelines have

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Table 2 Groundwater protection zones according to the Swiss water regulations (WPO 1998)

S1 zone: wellhead protection zone	This zone must prevent damage to the groundwater supply or artificial recharge facilities, as well as prevent pollution in its immediate surroundings
S2 zone: inner protection zone	This zone defines an area suitable for preventing germs and viruses reaching the groundwater supplies. The S2 zone must also prevent drinking water supplies from being polluted by excavation and subsurface works. Moreover, the flow of water towards the source should not be disturbed by subsurface works
S3 zone: outer protection zone	This zone must provide sufficient space and time for remediation when accidental pollution threatens a groundwater supply

thus been developed for delineating protection zones in karst (Doerfliger et al 1999; SAEFL 2000) and in fractured media (Pochon and Zwahlen 2003; Pochon et al. 2003). As the concept of protection zones is based on groundwater residence time, referring to the attenuation of bacteriological contaminant, an additional approach must be applied in the case of observed contamination linked to persistent substances (OFEFP 2005; Bussard et al. 2006).

Existing methods and need for a novel approach

The topic of delineation of protection zones, specifically for springs but regardless of the aquifer type, has been addressed by general guidelines (Jensen et al. 1997) and by the study of selected aspects such as the evaluation of the protective function of soil (Mania et al. 1998). The importance of establishing a hydrogeological conceptual model based on geological and hydrogeological data, as well as delineating the spring catchment area, has been emphasized (Jensen et al. 1997; Barton et al. 1999). In the case of heterogeneous aquifer properties, hydrogeological mapping or groundwater vulnerability mapping approaches may be indispensable in order to delineate protection zones (Jensen et al. 1997; Hemmer and Beach 1997).

Several methods for delineating protection zones in fractured media have been proposed in specific guidelines (Bradbury et al. 1991) or have been included in guidelines covering all aquifer types (Burgess and Fletcher 1998). However, they are generally focused on well protection and therefore are not directly applicable to springs. Various techniques and methods including tracer experiments (Robinson and Barker 2000) and vulnerability mapping approaches (Lipponen 2007) have been applied to groundwater protection zone delineation in several fractured aquifer case studies. However, criteria for choosing one technique over another, and for selecting the adequate method for protection zoning, are generally not specified.

In Switzerland, drinking water supplies linked to fractured aquifers essentially consist of small springs located in mountainous regions, and pumping test or piezometric data are therefore not available. Methods based on aquifer testing or groundwater modelling are consequently not applicable. Accordingly, the delineation of protection zones requires that other types of data are taken into account and the development of specific approaches. Although some of the methods and concepts mentioned in the literature can be applied in Switzerland, a novel approach was developed to meet the requirements of Swiss regulations. Due to the great diversity of geological and hydrogeological conditions observed in fractured media in Switzerland (Table 1; Fig. 2b and c), it is not possible to delineate protection zones for such aquifers using a single method. The presented approach uses consistent criteria firstly for selecting the appropriate

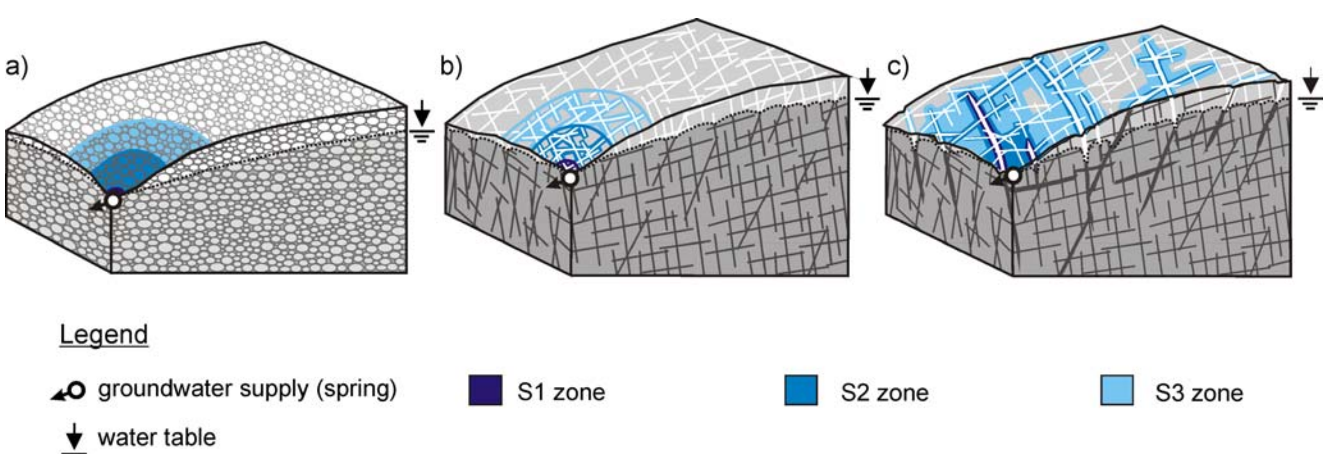

Fig. 2 Explanatory diagram of three aquifers with increasing heterogeneity. **a** Homogeneous porous aquifer; **b** fractured aquifer, slightly heterogeneous; **c** fractured aquifer, highly heterogeneous. Groundwater protection zones (*S1, S2, S3*) around the groundwater supply (spring) are represented for each case

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method and secondly for proposing a reliable procedure for the delineation of protection zones in each case. For this purpose, diverse existing techniques and concepts applicable to fractured rocks have been considered.

Main concepts and definitions

Aquifer global characterization: spring monitoring

Within the framework of protection zone delineation, it is essential to obtain data concerning the hydraulic properties of the aquifer. When considering springs, interpreting the natural response to recharge events at the discharge area is the most appropriate way of globally evaluating the aquifer properties and compensating for the lack of pumping test data.

Hydrograph analysis was initially applied to rivers and permitted the separation of fast flow components linked to runoff from retarded flow components linked to soil, as well as baseflow components linked to groundwater exfiltration (Barnes 1939). The same method, using the fitting of an exponential decay function to the observed data, was applied to karst springs to evaluate the volume and the recession of groundwater reservoirs with different permeabilities (Ford and Williams 2007; Baedke and Krothe 2001).

More comprehensive approaches, including the consideration of physico–chemical parameters (temperature, electrical conductivity, isotopes, chemical elements, turbidity) proved useful in better characterizing karst hydrogeological systems (Dreiss 1989; Sauter 1992). Spring hydrographs in non-karst fractured rocks have received less attention, but the same methods can be applied to characterize and compare crystalline aquifers (Gentry and Burbey 2004; Rossier and Sandmeier 1989).

Although these "global methods" are based on very simplified conceptual models, they allow the characterization and comparison of hydrogeological systems. Springs related to different aquifer types show clearly different hydrographs (Mangin 1982; Amit et al. 2002), i.e. on one hand the rapid evacuation of a high proportion of water infiltrated during a rain event in the presence of well developed karst or highly permeable fracture systems (e.g. a few days) and on the other the slow evacuation of freshly infiltrated water in the presence of less heterogeneous and less permeable systems (e.g. several months). Within the scope of the present approach, hydrographs and the variability of groundwater quality are used as a tool to evaluate, in a global manner, the *vulnerability of the springs* (Fig. 3; for definition see section Spring vulnerability versus vulnerability mapping). Specifically, the vulnerability of the spring is defined as low if no evidence of a significant amount of freshly infiltrated water is observed after an intense recharge event.

Aquifer spatial characterization: heterogeneity and vulnerability mapping

The spatial distribution of hydraulic properties is a crucial issue for the delineation of protection zones in fractured media (Bradbury et al. 1991). If no piezometric data are available, the main tool for determining the spatial characteristics of the aquifer is hydrogeological mapping and field testing (Jensen et al. 1997). Most field techniques include a qualitative interpretation of surface and subsurface features (geological, pedological, geomorphological and geophysical survey), which are interpreted in terms of hydraulic properties and which allow some groundwater flow hypotheses to be proposed.

Artificial tracer tests are often the only tool available to precisely determine groundwater velocity and to forecast contaminant flow in aquifers (Käss 1998; Field 1999). Most tracer experiments performed in fractured rocks presented in the literature involve the injection of tracers in boreholes with sampling at wells (Robinson and Barker 2000), galleries (Bäumle et al. 2001) or springs (Maloszewski et al. 1999). Many experiments have been performed with a focus either on a single fracture (Novakowski et al. 2004) or at the scale of a block including several fractures (Abelin et al 1991). Such experiments permit precise characterization of groundwater flow and solute transport at the small scale, but little information is available regarding tracer experiments including

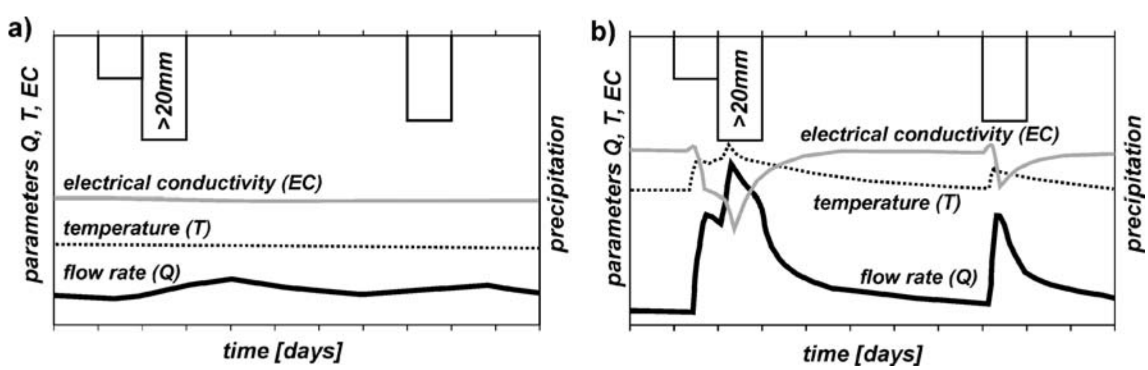

Fig. 3 Hypothetical example of spring hydrograph. **a** Low spring vulnerability; **b** high spring vulnerability

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injection on soil or in sinking streams while sampling at springs. Tracer testing has been widely used in karst environments to explore conduit flow at the scale of spring water catchment areas (Smart 1988; Ford and Williams 2007) but such experiments are less common for the characterization of the fracture network around non-karst springs. Even if flow velocities and recovery rates are generally lower in fractured aquifers than in karst aquifers, some experiments performed in mountainous regions revealed flow velocities in excess of 100 m/day over distances of several hundreds of metres in non-karstified aquifers (Maloszewski et al. 1999; Besson 1990). By comparing the results of different tracer tests, it is possible to evaluate aquifer heterogeneity and to correlate surface or subsurface features with observed groundwater flow velocities towards the spring. Thus, groundwater flow velocity hypotheses and hydrogeological maps can be locally verified and validated by quantitative data.

In the presence of highly heterogeneous aquifers and very high local flow velocities along fractures revealed by tracer experiments, *groundwater vulnerability mapping* appears to be the only method that can be reasonably applied to delineate groundwater protection zones. In such contexts, methods based on the determination of isochrones in the saturated zone would result in very wide protection zones, involving unnecessarily restrictive land use across extended areas. In contrast, vulnerability mapping permits the identification of areas less sensitive to contamination, where more intensive activities could be accepted without compromising groundwater quality.

Spring vulnerability versus vulnerability mapping

The term "vulnerability" refers to an intrinsic property of an aquifer which is dependent on its sensitivity to natural and human impacts, irrespective of the nature of the contaminant (Daly et al. 2002; Zwahlen 2004). This concept of groundwater vulnerability, defined either globally for a spring or spatially, is central for the approach developed for delineating protection zones in fractured media (see section Decision process for method selection). The term "spring vulnerability" is defined herein with reference to a global characterization of the aquifer and allows the attribution of a unique degree of vulnerability to the whole catchment area supplying the spring. The aim is to determine whether a spring is vulnerable to pollution without considering the range of vulnerabilities within its catchment area. Specifically, the question is whether a significant proportion of freshly infiltrated water quickly reaches the spring (high spring vulnerability) or not (low spring vulnerability) during a recharge event. This is achieved by performing discharge and water quality measurements.

A low spring vulnerability is determined if the following conditions are met (Fig. 3a):

- Spring discharge only varies with marked inertia and low amplitude to recharge events without significant relative variation of physico–chemical parameters (not clearly exceeding the analytical error or fluctuating according to seasonal trends).
- No significant turbidity is observed even after intense recharge events and no sediment deposits accumulate in the spring pool.
- Bacterial contamination is never detected.

A high spring vulnerability is determined if any of the above conditions is not met (Fig. 3b).

On the other hand, when considering "vulnerability mapping methods", vulnerability is determined spatially by evaluation and mapping of relevant parameters. In this case, the vulnerability is determined separately for each surface element of the catchment area. The concept of groundwater vulnerability mapping has been extensively used for different types of aquifers using various evaluation criteria (Vrba and Zaporozec 1994). Parameters taken into account may include: soil thickness and hydraulic conductivity, aquifer type and hydraulic conductivity, depth to groundwater level and net recharge, among others (Aller et al. 1987; Adams and Foster 1992). These maps were initially useful in providing a decision tool for land use planning and community information (NRC 1993). Recently, some groundwater vulnerability mapping methods have been developed to delineate groundwater protection zones around springs or wells, especially in karst settings (SAEFL 2000; DoELG/EPA/GSI 1999; Zwahlen 2004).

Unlike other methods which set out to delineate protection zones, vulnerability mapping methods take the protective effect of the unsaturated zone into account and assign less significance to transit times (which are included qualitatively in parameter evaluation, but are not directly evaluated). Ignoring transit times in the presence of highly permeable fractures is justified due to the limited filtration and sorption capacities along fractures and conduits, which suggest a significantly lower attenuation of bacteriological contamination compared to other media for the same residence time (Becker et al. 2003). Higher significance is therefore given to soil cover in view of the filtration and degradation properties of these layers (Golwer 1983). Interest in groundwater vulnerability mapping as a tool to delineate protection zones is particularly evident in highly heterogeneous media such as karst or highly permeable fractured aquifers, where the delineation of protection zones based exclusively on transit time in the saturated zone would result in the determination of excessively restrictive protection zones over large distances (e.g. several kilometres). In such cases, the consideration of the protective function of layers covering the aquifers (e.g. thick soils, moraine deposits) and/or the determination of less fractured areas, may permit the designation of locally less restrictive protection zones within the spring catchment area, thus allowing the coexistence of viable economic activities (agriculture, tourism) and the exploitation of groundwater.

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Decision process for method selection

Overview

The development of new guidelines for the delineation of protection zones in fractured media requires consideration of the varying properties of fractured aquifers exploited in Switzerland whilst applying a scientifically justified approach which is also user-friendly, financially affordable and avoids unnecessary land use restrictions. The recommended approach involves more or less detailed investigation depending on the complexity of the case. A suitable method for delineating groundwater protection zones is selected according to spring vulnerability and aquifer heterogeneity (Fig. 4).

Evaluation of the spring vulnerability: basic data acquisition

The first stage includes the collection and the interpretation of basic data about the aquifer. Monitoring of discharge rate, physico–chemical and microbiological parameters, turbidity, including observations in various hydrological conditions, allows the global vulnerability of the spring to be evaluated. Although continuous monitoring of discharge and physico–chemical parameters is becoming increasingly feasible in technical terms and economically affordable, and is therefore highly advisable, only a basic evaluation of spring hydrographs is required in the initial phase. This "qualitative" evaluation of spring hydrographs includes monthly measurements of discharge, temperature and electrical conductivity, complemented by more detailed monitoring (e.g. one measurement per day over three successive days) of the same parameters during an intense flood event (e.g. > 20 mm of daily precipitation in a period with limited soil water deficit). Additionally, several more detailed analyses (e.g. three samplings) including bacteriological, chemical, and turbidity measurements in adverse conditions are required. At least one detailed analysis must be performed after a high recharge event occurring during a period of intense potentially polluting activities (e. g. fertilizer or manure application).

Spring vulnerability is assessed as low if no groundwater with short residence time contributes to spring discharge at all, even during flood events. This situation is characterized by a non-significant temporal variability in spring discharge, temperature and electrical conductivity (Fig. 3a) and by an undisputable water quality (bacteriology, turbidity). Spring vulnerability is assessed as high once a significant proportion of groundwater with short residence time contributes to spring discharge during flood events (even in the range of

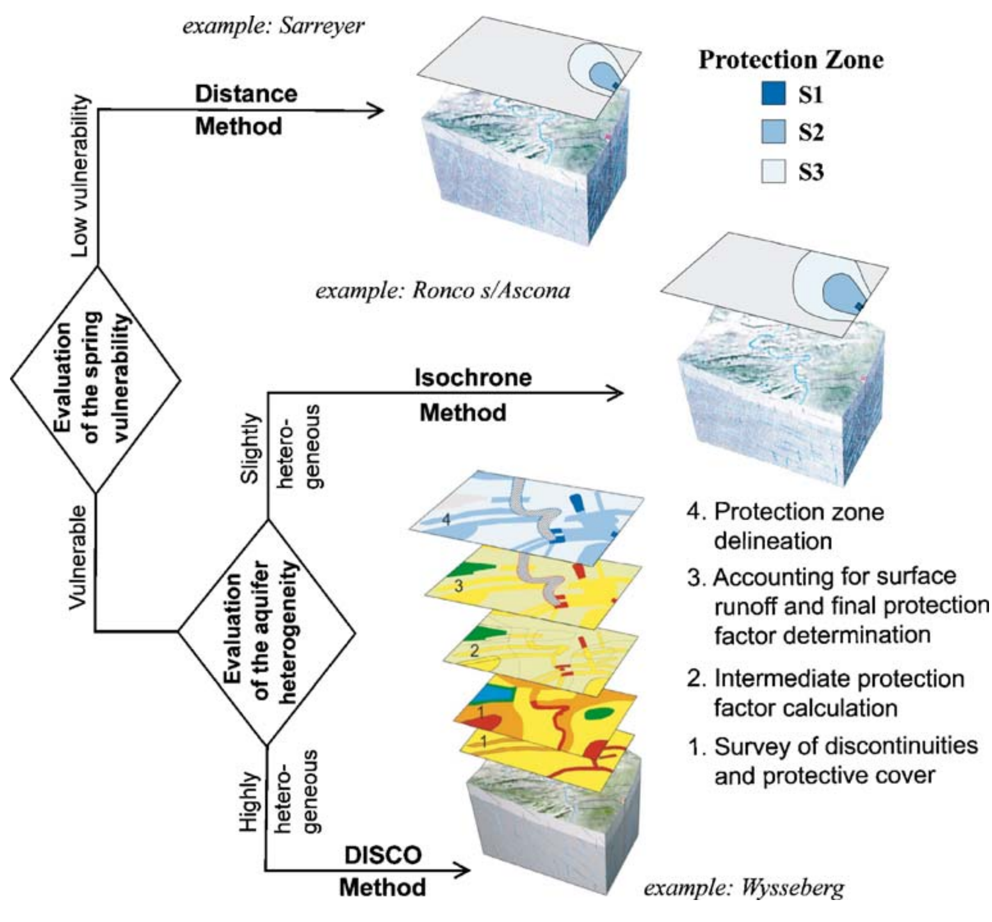

Fig. 4 Decision process allowing the selection of one of three specific methods to delineate groundwater protection zones in fractured media (after OFEFP 2004). The examples are presented in the text

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some percents). This situation is characterized by detectable variations of groundwater discharge, temperature and electrical conductivity implying the presence of locally high flow velocities within the aquifer (Fig. 3b). If the spring vulnerability is low, protection zones can be defined with a minimum size according to the Swiss regulations (extent of the S2 zone: 100 m), without any additional investigation (distance method, Fig. 4, see section Low vulnerability springs). For vulnerable springs, a second investigation stage is required.

Evaluation of aquifer heterogeneity: additional investigations

Only in the case of vulnerable springs must a second stage of field survey be carried out. The following additional investigations may be required: detailed analysis of rock jointing in the groundwater catchment area, identification of concentrated infiltration zones, continuous spring monitoring and detailed analysis of groundwater discharge, temperature and electrical conductivity time series, as well as tracer testing. These data allow more precise information concerning groundwater flow organization and the degree of aquifer heterogeneity to be obtained. If the spring is vulnerable and the degree of heterogeneity is found to be low, the residence time of groundwater in the network of connected joints is expected to increase in relation to distance from the spring. In this case, the protection zones are delineated by means of isochrones (isochrone method, Fig. 4, see section Vulnerable springs in slightly heterogeneous aquifers) on the basis of tracer testing. If the groundwater supply is vulnerable and the aquifer is highly heterogeneous, rapid hydraulic connections between vulnerable points located in any part of the catchment area and the spring may be possible; the residence time of groundwater in a highly permeable fracture network does not significantly increase with distance from the spring. In this case, a multi-parameter groundwater vulnerability mapping method is applied ("DISCO" method, Fig. 4, see section Vulnerable springs in slightly heterogeneous aquifers). The three methods are presented into more detail and illustrated by examples in the following chapter.

Methods and examples

Low vulnerability springs

Distance method

The distance method (fixed radius) is applied when the low vulnerability of the spring is demonstrated. In this case, groundwater residence time is assumed to be sufficient to allow natural purification processes to take place. Such springs can be related both to homogeneous and heterogeneous aquifers (e.g. confined in the discharge area; associated with a deep flow system drained by regional fractures). In these types of hydrogeological setting, tracer tests are often unsuccessful (no tracer recovery occurs even after several weeks) and do not represent an adequate investigation method. Only the collection of basic data is needed and small protection zones are sufficient to guarantee the quality of the exploited water.

In a simplified manner, this method considers the fractured aquifer as a continuous medium at the scale of the spring groundwater catchment area. The delineation of the protection zones according to the minimum distance defined for non-consolidated porous media by the Swiss water regulations is adequate to efficiently protect the groundwater supply (WPO 1998):

S1 zone. This zone must extend for a minimum at 10 m around or upstream of a spring and must incorporate drains, draining trenches or galleries.

S2 zone. The distance between the external limits of the S1 and the S2 zones must be at least 100 m upstream, considering the general groundwater flow direction.

S3 zone. The distance between the external limits of the S2 and the S3 zones must be at least equal to the distance between the outer limits of the S1 and S2 zones.

Test site application

The Sarreyer test site is located in the western part of the Swiss Alps (Canton Valais). The aquifer consists of metamorphic gneiss and schists, and groundwater is collected from four subhorizontal drains measuring 20–30 m. Water quality is good throughout the year and no significant variation of discharge, electrical conductivity or quality has been observed even during heavy rainfall. This suggests a low spring vulnerability.

Due to the subhorizontal drains, the extension defined for S1 is approx. 40 m. The S2 zone extends between 40 m (external limit of S1) and 140 m from the spring and the S3 zone is defined between 140 m (external limit of S2) and 240 m from the spring (Fig. 5).

Vulnerable springs in slightly heterogeneous aquifers

Isochrone method

The isochrone method (calculated radius) is applied to the case of vulnerable springs linked to slightly heterogeneous aquifers. In such contexts, some water may discharge at the spring after short residence time without sufficient natural purification processes in the aquifer (even a proportion of some percent may alter the spring water quality). Additional investigations are therefore needed to better characterize the aquifer. As fractured media are generally heterogeneous at the local scale, tracer injection must be performed on the most permeable areas based on a detailed hydrogeological survey (geological mapping, geophysics, infiltration tests). The isochrone method is applied when groundwater flow velocities along fractures are typically moderate to high (maximum: a few tens of metres per day) and when flows are relatively uniform at the

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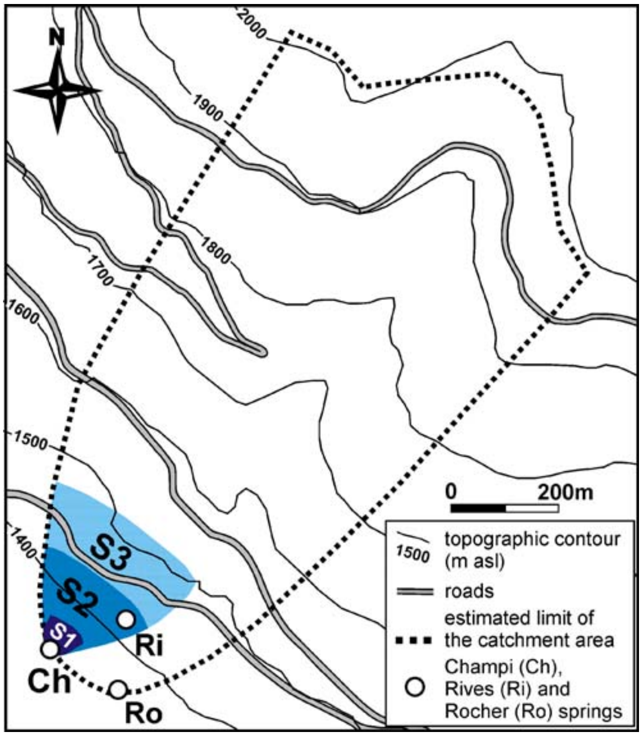

Fig. 5 Delineation of groundwater protection zones with the distance method for Champi Spring at Sarreyer

scale of the spring catchment area. The results of tracer injections performed at several favourable points during high water conditions allow determination of the isochrones.

When applying this method, the fractured aquifer is considered as a continuous medium at the scale of the groundwater catchment area. Therefore, the delineation of the protection zones is achieved according to the criteria recommended by the Swiss water regulations for unconsolidated porous media (WPO 1998):

S1 zone. This zone must extend to a minimum of 10 m around or upstream of a spring and must incorporate drains, draining trenches or galleries.

S2 zone. This zone is based on the evaluation of the maximum flow velocity in the aquifer. The 10-day isochrone must be defined and corresponds to the outer limit of the S2 zone. Moreover, the distance between the external limit of the S1 zone and the external limit of the S2 zone must be at least 100 m upstream, taking into account the general groundwater flow direction (Fig. 6).

S3 zone. The distance between the external limits of the S2 and the S3 zones must be at least equal to the distance between the outer limits of the S1 and S2 zones.

Test site application

The Ronco sopra Ascona test site is situated in the southern part of the Swiss Alps (Canton Ticino). The aquifer consists of metamorphic amphibolites and gabbros and the groundwater supply collects water discharging from a fracture. Significant variations in discharge, electrical conductivity and temperature are observed during the year and suggest that the spring is potentially vulnerable to contamination. Consequently additional investigations were carried out.

A field survey including structural geology, geomorphology observations, geophysics and a multi-tracer experiment led to the conclusion that the degree of aquifer heterogeneity is low. Fracturing is distributed evenly across the catchment area with a spacing of approx. 10 to 20 m. However, rock permeability and flow velocities were assumed to be variable at the small scale. Therefore, tracer testing was performed on two potentially highly permeable areas (fractured zones). The fluorescent dyes tinopal and uranine (Käss 1998) were injected respectively 20 and 90 m from the spring. To account for a probable increase of flow velocities during high water conditions, the experiment was conducted during an intense recharge event. Moderate flow velocities of 12 and 15 m/day respectively were determined. Moreover continuous monitoring of discharge, electrical conductivity and temperature over a

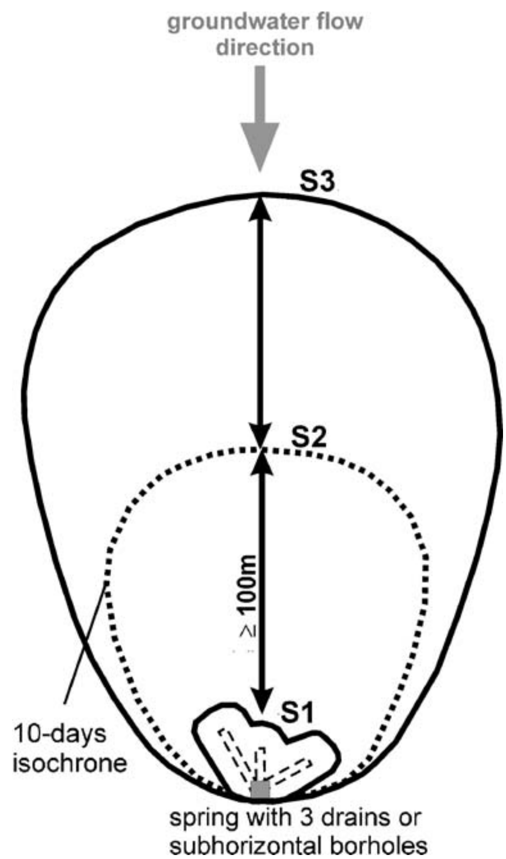

Fig. 6 Principle of the delineation of groundwater protection zones with the isochrone method for relatively homogeneous fractured aquifers

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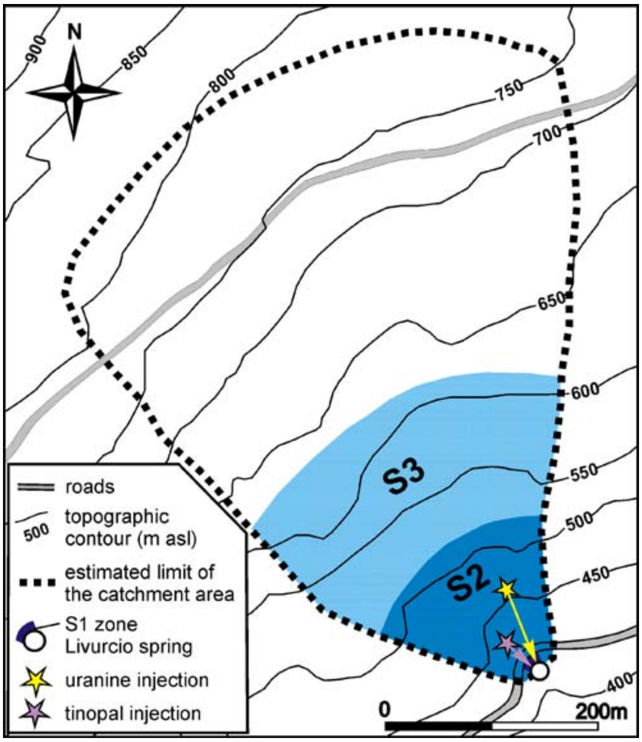

Fig. 7 Delineation of groundwater protection zones with the isochrone method, Livurcio Spring at Ronco sopra Ascona, based on tracer experiments

period of several months suggested a significant inertia of the spring to recharge events, illustrated by slow recession curves (1 month to return to the base flow after a significant recharge period of approx. 250 mm of precipitation over 5 days). It was also determined that there was no significant variation in temperature and electrical conductivity during moderate recharge events (10 to 20 mm).

As water is collected from a small fracture discharging into the catchment facility, an S1 zone extending 10 m from the spring was considered to be sufficient. The distance between the external limits of the S1 and the S2 zones was set at 150 m based on the maximum flow velocity determined by tracer tests (15 m/day). Accordingly, the S3 zone extends from 160 to 310 m from the spring (Fig. 7).

Vulnerable springs in highly heterogeneous aquifers

DISCO method

The DISCO method (groundwater vulnerability mapping method) is applied in the case of vulnerable springs linked to a highly heterogeneous aquifer. In such contexts, a significant proportion of water discharges at the spring after a short residence time in the aquifer, preventing sufficient natural purification processes to take place. Additional investigations are needed and tracer testing typically reveals locally very high flow velocities (up to several hundreds of metres per day). In this case, a groundwater vulnerability mapping method is applied to the whole catchment area of the spring. The parameters taken into account in the DISCO method include characterization of hydrogeological properties of the fractured aquifer (DIScontinuities parameter) and evaluation of the thickness and permeability of protective cover (protective COver parameter). Moreover, taking runoff processes into account may be required for some areas, where surface movement of polluted water towards preferential infiltration zones is expected. A protection factor map is determined by combining the different parameter maps and the protection zones are finally determined by converting the protection factor map into protection zones. Consequently, the multi-parameter vulnerability mapping method includes four steps as follows:

Step 1 Assessment of the parameters “discontinuities” and “protective cover”.

This first step consists of the evaluation and mapping of the parameters “discontinuities” and “protective cover” over the whole catchment area, subdivided into areas of uniform properties for each of the parameters. The parameter “discontinuities” referred to below as “D” takes into account the groundwater flow velocity within the fractured aquifer between an infiltration point in the water catchment area and the spring under consideration (e.g. highly permeable fractured zone with rapid connection to the spring versus weakly fractured area). The evaluation of the parameter “D” is essentially based on structural geology (field survey and remote sensing), geophysics and tracer experiments. The rating values of “D” range from 0 to 3, with increasing values corresponding to higher residence time and attenuation

Table 3 “Discontinuities” parameter evaluation

Class	Rating	Evaluation criterion
D_0	0	Highly permeable discontinuities with preferential connection to the spring (maximum groundwater residence time of a few tens of hours) / no significant natural purification processes
D_1	1	Discontinuities with a relatively rapid connection to the spring (residence time of a few days) / limited purification processes
D_2	2	Discontinuities with a relatively slow connection to the spring (residence time of approx. ten days) / significant purification processes
D_3	3	Low permeability zone or discontinuities with a slow connection to the spring (residence time of several tens of days) / efficient purification processes

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Table 4 "Protective cover" parameter evaluation taking into consideration pedological soil overlying the aquifer

Pedological soils						
Thickness (m)	High permeability soil (sand, pebbles)		Moderate permeability soil (silt, loam)		Low permeability soil (loam, clay)	
	Class	Rating	Class	Rating	Class	Rating
0.0–0.2	P_0	0	P_0	0	P_0	0
> 0.2–0.5	P_0	0	P_0	0	P_1	1
> 0.5–1.0	P_0	0	P_1	1	P_2	2
> 1.0	P_1	1	P_1	1	P_3	3

processes (Table 3). The parameter "protective cover" referred to below as "P" takes into account the protective effect linked to the flow of water through the soil and geological formations (e.g. moraine, slope deposits, marls, clay material) overlying the fissured aquifer. Data necessary for the evaluation of the parameter "P" may be assessed using hand drilling, on-site soil analysis, geomorphological mapping (field survey and remote sensing), geophysics and infiltration tests. The rating values of "P" range from 0 to 4, with increasing values corresponding both to higher protective cover thickness or/and lower permeability of the deposits (Tables 4 and 5). The ratings were defined based on field studies at numerous test sites. It takes the feasibility and constraints of field methods (e.g. maximal depth of hand drilling) for each parameter into account, as well as groundwater velocity estimate for different types of soil and fractured rock.

Step 2 Determination of the intermediate protection factor "F_{int}".

For each polygon presenting uniform values for the parameters D and P, the protection factor F_{int} is calculated as follows:

$$F_{int} = 2D + 1P$$

This empirical relationship is based on the assumption that the protective effect related to the fractured aquifer as described in Table 3 is greater than the protective effect of the soil as described in Tables 4 and 5.

Step 3 Evaluation of the runoff parameter and calculation of the final protection factor "F".

Surface or subsurface runoff can generate rapid contaminant flow over several tens (diffuse runoff) or hundreds of metres (e.g. presence of natural or artificial drain, perennial or temporary stream, path or road). Since the majority of fractured aquifers exploited in Switzerland are located in mountainous regions, it is essential to take these processes into consideration. Unlike the parameters "discontinuities" and "protective cover", which are mapped over the whole catchment area, the runoff parameter is only considered for areas where runoff may induce substantial pollutant movement toward vulnerable zones, i.e. where the intermediate protection factor value is low or very low ($0 \leq F_{int} \leq 4$). The extent of these areas ("local surface watersheds") is determined by estimating the influence of runoff, i.e. slope gradient and soil permeability, etc. (Fig. 8). Evaluation of these factors requires field observation during intense rainfall events.

The final protection factor map is obtained by modifying the intermediate protection factor map (obtained under step 2) according to the already mentioned local surface watersheds. In these areas, the value of the intermediate protection factor F_{int} for the vulnerable zones threatened by runoff is extended to cover the whole local surface watershed. Outside these local surface watersheds, the final protection factor F remains the same as the intermediate protection factor F_{int} determined in step 2.

Step 4 Protection zone delineation. The final protection factor "F" map is converted into protection zones S according to the relationship presented in Table 6.

In all cases, spring drains, draining trenches and galleries as well as their immediate surroundings must be part of the S1 zone, with a buffer of 10–30 m depending on the gradient of the slope. Additionally, as a precautionary measure, no S3 zone must be defined at a distance of less than 100 m from the outer limit of the S1

Table 5 "Protective cover" parameter evaluation taking into consideration geological formations other than pedological soils overlying the aquifer

Additional presence of low permeability formations (e.g. clay, loam, marl)								
Thickness (m)	Combined with P_0 soil		Combined with P_1 soil		Combined with P_2 soil		Combined with P_3 soil	
	Class	Rating	Class	Rating	Class	Rating	Class	Rating
< 1.0 m	P_1	1	P_2	2	P_3	3	P_3	3
1.0–2.0 m	P_2	2	P_3	3	P_3	3	P_4	4
> 2.0 m	P_3	3	P_3	3	P_4	4	P_4	4

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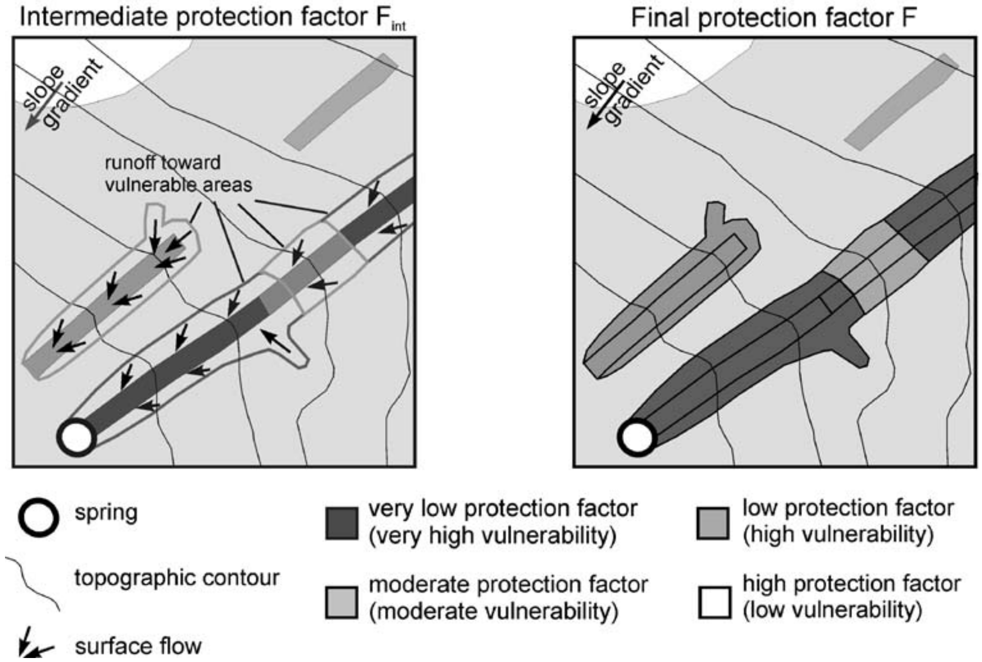

Fig. 8 Modification of the intermediate protection factor to take runoff processes into account

zone adjacent to the water supply, and no area corresponding to the "rest of the catchment area" should be defined closer than 200 m to this S1 zone boundary.

Test site application

The Wysseberg test site is located in the Swiss Prealps to the south of Bern (flysch of the Niesen Nappe, Canton of Bern). The aquifer consists of folded and fractured flysch sandstones and schists (Fig. 9a). Groundwater protection zones have been delineated for two groups of springs (three springs to the east, five springs to the west), as explained below. The springs are aligned along major fractures. They collect groundwater from the fractured bedrock and from weathered flysch at shallow depths (approx. 2 m). The aquifer is covered by approx. 1 m of brown soil with high proportions of silt and clay in the bottom layer. Additionally, ground and lateral moraine as well as slope deposits (scree) are present locally. The limits of the groundwater catchment area were defined according to topographical and geological criteria and have been verified with a water balance calculation. Cattle rearing and manure spreading between June and September represent the main pollution hazards upstream of the springs. Significant fluctuations in spring discharge, water temperature and electrical conductivity, as well as indications of bacteriological contamination, even in winter, have been observed. Consequently, the springs appear to be vulnerable to contamination and additional investigations are needed.

Table 6 Conversion between the protection factor F and the groundwater protection zones

Protection factor F	Vulnerability	S zones
F very low (0, 1)	Very high	S1
F low (2, 3, 4)	High	S2
F moderate (5, 6, 7)	Moderate	S3
F high (8, 9, 10)	Low	Rest of the catchment area

Various systems of structural discontinuities at the scale of the groundwater catchment as well as at outcrop level have been observed. They dictate the location of the springs. Geomorphological depressions constitute potential locations of concentrated infiltration and open fractures are apparent along stream beds. Tracer tests have shown highly variable flow velocities for different injection points in the spring catchment (50–600 m/day). All these data indicate the presence of rapid flow along interconnected networks of highly permeable joints. Rapid connections are possible between the springs and surfaces that may be distributed across the whole catchment area of the spring. Consequently, the groundwater residence time does not increase globally or significantly with increasing distance from the spring, and an assimilation of the fissured aquifer to a continuous medium is inappropriate. Under these conditions, only the use of a multi-parameter groundwater vulnerability mapping method over the whole catchment area enables effective delineation of protection zones by taking into account the large degree of heterogeneity within the aquifer.

With reference to the delineation of protection zones at Wysseberg test site, strips of 20–30 m in width with the value D_1 were assigned along the major faults for the parameter discontinuities (Fig. 9b). The value D_2 was assigned to the rest of the groundwater catchment. For the parameter protective cover (Fig. 9c), surfaces of aquifer outcrops (P_0), surfaces covered with soil only (P_1, P_2) and surfaces with an overlay of moraine material (P_3) were

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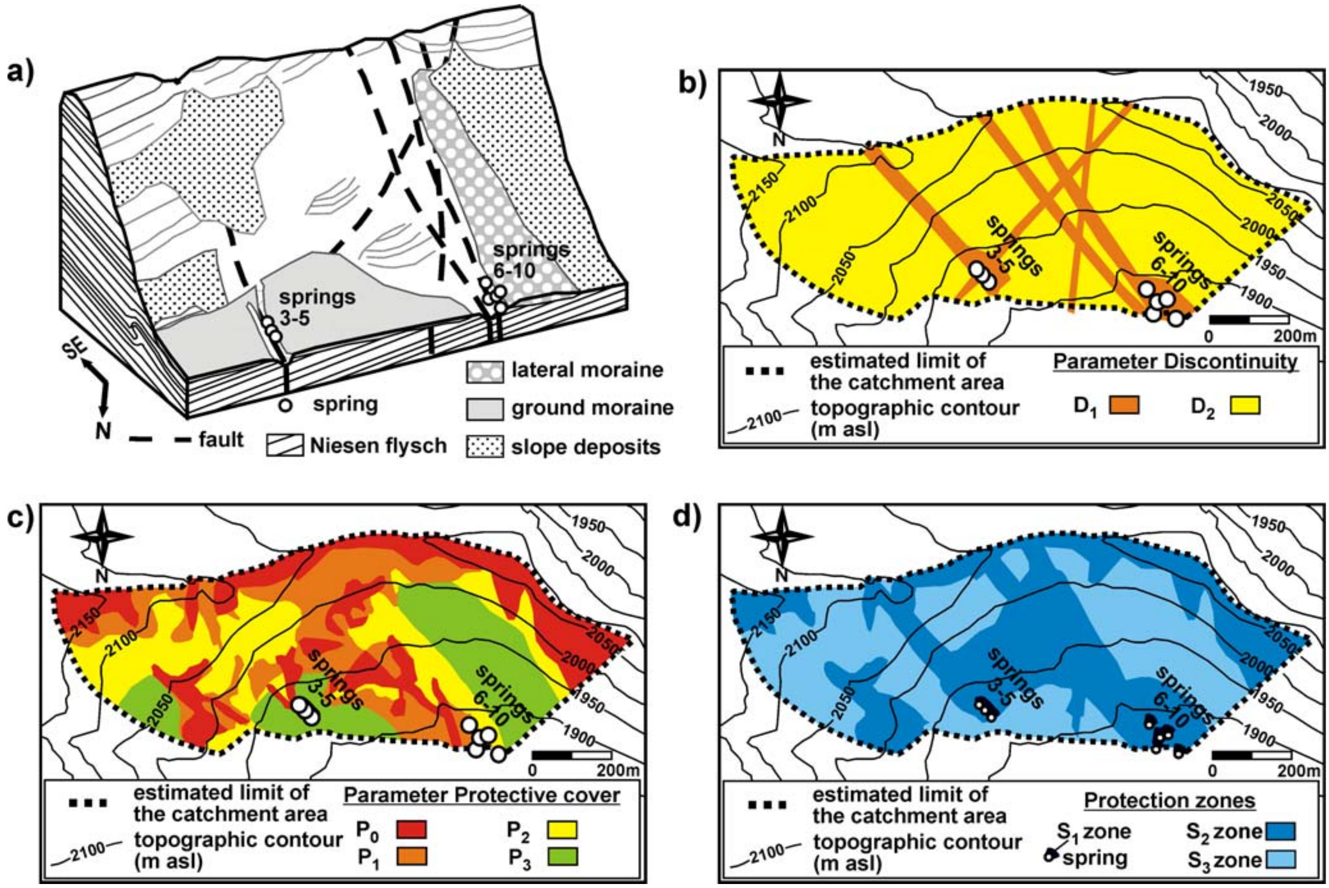

Fig. 9 Wysseberg test site. **a** Bloc diagram showing the geological setting; **b** discontinuities parameter map; **c** protective cover parameter map; **d** delineation of groundwater protection zones with the DISCO method

mapped. Accordingly, the value determined for F_{int} ranges from 3 (low protective effect) to 7 (moderate protective effect).

Due to the slope topography and the presence of low permeability cover over large parts of the groundwater catchment area at the site, it was necessary to adjust the F_{int} map, taking the runoff parameter into account. Finally, the protection zone map (Fig 9d) shows that S2 zones were assigned to the most important draining discontinuities, taking into account the aquifer heterogeneity. S3 zones are only defined in areas characterized both by the absence of important fractures and the presence of efficient protective cover. Due to the presence of collecting drains of unknown extension and the relatively steep gradients of the slopes above the springs (10 to 20%), the S1 zones were extended to not less than 25 m.

Conclusions

In Switzerland, specific methodologies for the delineation of protection zones have been developed and are currently used for the main aquifer types (unconsolidated porous aquifers, karst and fractured media). For fractured media, a new vulnerability-based approach, which takes into account the great diversity of geological and hydrogeological conditions observed in this country, was established. This approach includes a decision process that alternatively selects one of three methods depending on the hydrogeological settings considered. It is dedicated to springs, which are the main water supply in fractured environments in Switzerland.

This approach has the advantage of globally assessing the spring vulnerability at an early stage of the investigation, allowing the selection of a simplified method (distance method) for uncomplicated cases (low spring vulnerability). In such hydrogeological settings characterized by high residence times and low flow velocities, detailed hydrogeological investigation would not bring useful additional data for the protection of the groundwater supply. More detailed investigation including tracer experiments and an evaluation of the aquifer's heterogeneity are required for more complicated cases (high spring vulnerability). The additional data obtained can be used to determine whether a method considering the aquifer as homogeneous can be applied (isochrone method), or whether vulnerability mapping is necessary to adequately delineate spring protection zones, i.e. for highly heterogeneous media (DISCO method).

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Investigations carried out at various test sites have shown the technical feasibility and the suitability of the vulnerability-based approach for fulfilling the requirements of the Swiss regulations concerning groundwater protection zones. It is applicable to the variable conditions encountered across the whole country, and gives reproducible results with a financial effort proportionate to the complexity of the site. The methodology should facilitate a countrywide harmonization of the groundwater protection zone delineation in fractured media.

The Swiss environmental authorities recommend this methodology in their current guidelines (OFEFP 2004). The delineation of protection zones according to the proposed methodology and the application of associated land use restrictions is assumed to prevent the majority of spring contamination in fractured aquifers in Switzerland. However, a detailed analysis of the effectiveness of the approach will only be possible as more case studies are carried out and data from long-term groundwater quality monitoring become available.

It is assumed that this approach is also applicable to fractured media outside Switzerland. Furthermore, this concept may also be adapted to the delineation of protection zones around wells and to other aquifer types (e.g. deep and/or confined aquifers). The implementation of this approach is believed to contribute to a valuable improvement of spring drinking water quality in many regions. It is expected that ongoing research on fractured media hydrogeology and experience with additional applications of the approach and its associated methods will give significant input for further refinement.

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